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As proposed, two inverted echo sounders were deployed alongside two enhanced TOGA-COARE moorings in the western Pacific to be used in an in situ evaluation of TOPEX/Poseidon altimetric measurements of sea surface height. The locations and dates that data were obtained are as follows:

Site 1:	1°59.6'S	155°54.0'E	9/12/92 - 12/7/92
Site 2:	2°01.0'S	164°24.4'E	8/26/92 - 3/22/93

These data were then reduced under this grant and analyzed with funds provided by JPL grant no. 958123.

The result was the mooring and inverted echo sounder data reproduced one another, at low frequency, with a correlation of 0.93 and 0.95 and the altimeter correlated with each of the above with values ranging from 0.84 to 0.94. The conclusion is that the altimetric measurements are statistically equivalent to the in situ measurements in the area of study. This work resulted in a paper submitted September 1994 to the *Journal of Geophysical Research* entitled **A Comparison of Coincidental Time Series of the**

(NASA-CR-198621) [AN IN SITU EVALUATION OF TOPEX/POSEIDON ALTIMETRIC MEASUREMENTS VERSUS MEAUREMENTS MADE BY MOORINGS AND INVERTED ECHO SOUNDERS FOR SEA SURFACE HEIGHT] Final Report (Lamont-Doherty Geological Observatory) 25 p

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Ocean Surface Height by Satellite Altimter, Mooring, and Inverted Echo Sounder authored by myself and the following co-authors:

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A copy of a final draft of that paper is attached and it completes this report.

Yours respectfully,

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Enclosure

EJK/msc

A Comparison of Coincidental Time Series of the Ocean Surface Height by Satellite Altimeter, Mooring, and Inverted Echo Sounder

by

Eli Joel Katz, Antonio Busalacchi, Mark Bushnell, Frank Gonzalez, Lionel Gourdeau, Michael McPhaden, and Joel Picaut

Abstract

Satellite altimeter data at two locations in the western tropical Pacific Ocean are compared to estimates of the dynamic sea surface height computed from cotemporal surface-to-bottom temperature/salinity measurements on moorings and acoustic travel time measured by bottom-moored inverted echo sounders. The results show statistically high correlation between the in situ measurements themselves (excluding the highest frequency variations) and between the altimeter and in situ measurements at periods greater than twenty days. The rms difference between any two modes of observation is consistently between 2 - 3 cm.

I. Introduction:

The classical method of observing the sea surface height has been to make shipboard measurements of the vertical - density profile, and then calculating the surface height relative to a deeper reference surface. Beginning in the 1920's, the profile was estimated from sampling at a discrete number of depths with Nansen bottles and, by mid-century, better vertical resolution was achieved by lowering continuously sensing instruments. To obtain a time series at a site required the ship to either remain there or continuously revisit the site and understandably few series were obtained.

Two methods (a moored vertical string of instruments and an inverted echo sounder) were subsequently developed to obtain longer time in situ measurements. The first of these can be thought of as an extension of the discrete bottle hydrocast while the second integrates acoustically over the water column. One purpose of this note is to compare the result when coincidental observations are made by these two methods. This will be done at two sites in the western tropical Pacific.

The future, with satellite altimetry capable of providing a continuous, near-global, observation of sea surface height, promises a change in how the oceans can be studied. However, it is first essential that the accuracy and possible limitations of altimetry be understood. The primary purpose of this note is thus to compare the time variability of the dynamic height of the sea surface as determined from in situ measurements with coincidental altimeter observations.

Two TOGA-TAO moorings were deployed with additional instruments along 2°S to coincide with crossing points of two pairs of TP (TOPEX/Poseidon) paths at 156°E and 164°E. Three inverted echo sounders were deployed (two at 156°E). The exact locations and deployment/recovery dates are given in Table 1. The ocean depth at the two sites is 1.7 and 4.4 km, respectively. Their location relative to the relevant altimeter paths are shown in Figure 1.

The comparison is not thought to be particularly site dependent. However, the location in the tropics is characterized by a large amplitude M_2 tidal component (one half meter) and only average annual sea surface variability (20 centimeters). These two conditions combine to make this a better than average location to evaluate the altimeter which relies on tidal models to remove what could otherwise be severe tidal aliasing.

II. Data Description and Reduction.

Each of the methods of observations respond differently (or not at all) to various time dependent, vertical displacements, in the water column. For example, individual instruments on the mooring (with sample rates as fast as 5 minutes), will sense the presence of internal gravity waves. They, and the echo sounders, will be influenced by the internal tides and inertial-gravity waves. All are influenced by the barotropic tide, but to a different extent and comparison requires a special analysis. Some of these signals will be discussed in a companion paper [Picaut et al., 1995] but our purpose here is to focus on their common window of observation.

Quantitative comparison between the three modes of observation therefore require appropriate low-pass filtering.

A. *Moorings*

The two moorings were deployed by the NOAA Pacific Marine Environmental Laboratory and the ORSTOM laboratory in New Caledonia. They consisted of ATLAS moorings (ten temperature sensors which record daily mean temperature between the surface and 500 meters), augmented with:

i. 5/12 (shallow/deep site) mini-temperature recorders, below 500 m and approximately 500 m apart, recording at 5-minute intervals.
ii. 16/11 SEACAT temperature-salinity sensors with sampling intervals mostly at 5 mins.
iii. Pressure recorded at four depths between 300 and 750 meters (and from which the depth of each instrument was calculated) at 10-minute intervals.

All the time series were first interpolated to common 5-minute intervals, taking into account the high frequency variations from the surrounding instruments. Salinity, where available, was interpolated to the bracketed temperature sensors (taking into account the vertical movement of each sensor). Below 750 meters, a mean temperature-salinity relationship was used to assign a salinity to the observed temperature.

Each instrument was calibrated before and after the experiment, with little variation found. A linear interpolation in time was used to correct the final time series.

Surface dynamic height, relative to both 1000 dbars and the bottom-most sensor, was computed after reducing each time series back to hourly averages. As might be expected, there is no significant difference in the variance between the two calculations. At the 164°E (deeper) site for example, the following is obtained:

	range (mm)	rms(mm)
0/1000 db	229.8	48.0
0/4400 db	251.8	50.3

With less than 5% of the time variable signal in dynamic height originating below 1000 dbar, subsequent discussion is limited to surface height relative to that depth, however both are shown in the upper panel of Figure 2, after low-pass filtering.

B. *Inverted Echo Sounder.*

To calibrate the sounders, the recorded change in travel time, δt, is divided into two parts,

$$\delta t = \delta\left[\int_H^{z_o} \frac{dz}{c}\right]$$
$$= \left(\int_{z_r}^{z_o} + \int_H^{z_r}\right) \delta\left[\frac{1}{c}\right] dz ,$$

where c is the sound velocity at depth z, z_o is the free surface (defined as gage pressure = 0), H is the depth of the sounder and z_r is the depth of a reference pressure level. Assuming z_r to be a level of no motion, the first term is computed from historical hydrocasts in the region and the second term is ignored. That latter term contains two possible signals: changes in the temperature of the deeper waters and barotropic changes in the sea surface height. Aside from the barotropic tide both signals vary slowly relative to the baroclinically induced variability and are assumed to be uncorrelated with it. The barotropic tide, which is the largest part of the sounder signal, is removed by a low-pass filter without fear of aliasing given the sounder's high frequency sample rate.

With a reference level of 1000 dbars, the sea surface dynamic height and the travel time between it and the free surface were computed from two sets of hydrographic data and the result is show in Figure 3.

One set consists of thirty profiles in the vicinity of 2°S 165°E made from 1984 to 1991 (half during semi-annual cruises in January and July). The other is a time series of eighteen profiles at 2°S 156°E made in December 1992 - February 1993. The two sets are statistically indistinguishable, though the wider spread of data from 165°E reflects the fact that some of the observations were made during several strong, basin wide, interannual events (the 1986/7 and 1991/2 El Niño episodes).

The slope of the regression line of the combined data set is -77.9 mm/msec with a standard error of 3.0 mm/msec. Confirmation that this regression coefficient is not time dependent and is representative of an even larger geographic area comes from a comparison with the published results of Maul et al. [1988] in the eastern tropical Pacific. From 133 profiles to 1000 dbars in the area 0.5°S — 1.5°N, 105°W — 115°W, they computed the statistically equivalent value of —73.4 (±2.1) mm/msec.

The derived regression is used to approximate the changes in total travel time recorded by the sounder and the resulting time series of the three sounders were low-pass filtered. The result is shown in the middle panel of Figure 2. The two sounders at 156°E track one another well for the beginning of the record, and then diverge. The Lamont sounder (L in Table 1) was experiencing reset problems (which may have disturbed its timekeeping and was soon to shut down the instrument completely). It is shown here only to demonstrate the repeatability of the measurement by two separate instruments for the 70 days when they both were properly sampling, but comparison with the other modes of observation will use only the A sounder at this site.

C. *Altimeter*

The first usable data from TOPEX/Poseidon comes from passes over the observation sites on 13 October 1992, two months after launch and more than one month after the beginning of the in situ data. It is then continuously available from each "10-day" cycle until after the in situ instruments were recovered. The location of the tracks relative to the observation sites is shown in Figure 1. The satellite reports data at a rapid rate which translates into ten independent observations in a half degree band of latitude about the site. To reduce some of the measurement noise (and possibly small scale ocean variance), the surface height of the site is obtained by linear regression over the meridional band after occasional outliers are removed. The data going into that regression is exactly that obtained from the NASA MGDR discs (with corrections as recommended by the PO.DAAC Merged GDR Users' Handbook and using the NASA orbit) after subtracting 175 mm from the data of the occasional cycle when the Poseidon altimeter is on, to compensate for a reported instrument bias relative to the TOPEX altimeter.

Once the time series of each pass over each site were developed, two other adjustments were made before smoothing the data. First, the mean values of the time series were removed. This was done by pass, and not by site, because the mean values of the two passes over the 156°E site were found to vary by 140 mm, and this was thought to be an artifact of the introduction of the model geoid gradients along the two tracks. Secondly, the possibility of tidal aliasing had been taken into account. That is, if the tidal model used to remove the tide from the altimeter signal is not completely accurate, then there is a possibility of introducing a spurious signal (the accuracy of tide models is explored further in the Appendix). For the M_2 tide (frequency, f_{M2} = 1.932227 cycles/day) which dominates the barotropic tide in this area and the TOPEX sampling frequency (f_t) of (9.9156 days/cycle),$^{-1}$ the alias frequencies (f_a) are given by

$$f_a = (N \times f_t - f_{M2}), \text{ with N an integer.}$$

Only N = 19 gives a frequency within the spectral window of the altimeter (specifically, a period of 62. 1074 days, all other N yield periods of less than 12 days). Modulating each time series by e^{if_a} yielded amplitudes of 2.9 and 3.0 mm, and the time series were accordingly complex demodulated at those frequencies.

As a final step, before comparing the altimeter with the in situ observations, the altimeter data is bin-averaged over twenty days every five days and this result is shown in the lower panel of Figure 2, along with the unaveraged data. This last smoothing is to take into account that the altimeter data consists of two (unevenly spaced) observations every 10 days and it is therefore unable to resolve periods shorter than 20 days.

III. Comparisons

A. *Sounders vs. Moorings*

The sounders and mooring measurements have much in common, differing primarily in the methodology used to compute the surface dynamic height. The former relies strongly on the stability of the temperature — salinity correlation to effectively convert a vertically averaged temperature, over the entire water column, into an integrated density measurement. The latter (which also depends on the temperature — salinity assumption below 750m where no salinity measurements were made) assumes that the vertical distribution of sensors was sufficiently dense and properly distributed to accurately record the vertical integral it calculates from discrete points. The comparison between the two is indicative of the plausibility of their underlying assumptions where they differ.

In Figure 4, the spectral density of sea surface height from the two in situ methods at the two sites are compared. They resemble each other in the following ways: the high frequency end of the spectrum is dominated by the diurnal and semi-diurnal tidal motion. At mid-frequency, 3-5 day periods, there is an increase in variance from inertial gravity waves, as previously reported in the tropical Atlantic Ocean [Garzoli and Katz, 1981]. The low frequency end (beginning at periods of 10-20 days) shows a f^{-2} behavior which, by extrapolation from six-year records in the tropical Atlantic [Katz, 1993], would continue until the annual period. The quantitative comparisons between these observations and the altimeter will be restricted to this low frequency band.

The spectral density at the lowest frequencies are identical for the two observations at 164°E and for the sounder at 156°E. The mooring at the latter site appears to be higher but after noting that this is true for only the three lowest estimates, comparing their averages would give 3x5 (frequency bands averaged), or 15, degrees of freedom. The 95% confidence limits for this is shown on the figure and the average spectral estimates are found not to be significantly different.

To compare the moorings and sounders, the 5-day, low-pass filtered, data of each are shown superimposed in Figure 5a. This filtering removes the high frequency variations which enter differently into the two modes of observation. As noted in the spectral comparison, the observations at 164°E (the eastern, deep water, site) track better at low frequency.

Some statistical measures of the comparisons are given in Table 2. The correlation coefficient between the two signals at 164°E (L & M) is 0.86. Subtracting the sounder data from the mooring data removes 73% of the variance. Both of these measures are comparable to the result from the shorter, sounder versus sounder records (L & A), suggesting that the mooring and sounder record the same signal to 2 cm. (the rms of M-L), a number measuring the instrument/ocean noise of the two signals.

Unlike the comparison at 164°E, where mooring and sounder had rms values within 10% of one another, their rms differ by 50% at 156°E. Yet the reduction of variance and rms of their difference (62% and 2.5 cm) is comparable.

B. *Altimeter vs. Mooring/Sounder*

As noted earlier, to compare the altimeter to the in situ measurements, it is advisable to smooth the data sets over twenty-day periods. This was shown for the altimeter data (Fig. 2, lower panel) and in Figure 5b we compare it to the mooring and sounder data after processing them with the same running mean filter. The statistics of this comparison are also given in Table 2.

The rms height of the altimeter data is always higher than either of the in situ observations, but 63 to 77 percent of its variance is also present in the latter. The correlation coefficients are high

(0.84 to 0.94), and only slightly less than the mooring/sounder coefficient (0.93 and 0.95) at these low frequencies band.

IV. Summary and Conclusions:

The usual method for demonstrating the validity of the calibration of inverted echo sounder records is to compare them with dynamic height calculations from occasional contemporary hydrographic profiles. For example, Katz [1987] reported a standard deviation of 2.9 dynamic cm from 17 independent samples (in the tropical Atlantic). However, since the sounder is essentially a continuous observation while the profile is a snap shot, there is an uncertainty to how much of that deviation derives from high frequency variability that is necessarily smoothed out of the sounder record before making that comparison.

The comparison here, between the mooring and sounder, is not degraded by a difference in sampling rate. Both are essentially continuous sampling and the result is an rms difference of 2.0 and 2.5 dynamic cm. Without taking a position about which method (stations, moorings, or sounders) is "more accurate", the data indicate that they can reproduce each other to something between 2 and 3 cm.

This result then provides a quantitative measure with which to assess how well the TOPEX/Poseidon altimeter data tracks the sea surface height. (Here, as throughout, we assume that low frequency barotropic changes are small enough to be ignored). In Table 2, four comparisons between altimeter and in situ observations show an rms difference from 2.7 cm (compared with either of two moorings) and

3.3 cm (with either of two sounders). Thus we conclude that, at the frequencies resolvable by the altimeter, the altimeter yielded a time variable sea surface height (at our verification sites) at an accuracy statistically indistinguishable from our ability to measure that same variability by in situ methods.

Just as the orbit cycle time limits the altimeter to low frequencies, it also makes the accuracy one can expect from the altimeter very sensitive to the accuracy of the models of the relatively large amplitude, but under sampled, local tides. The latter were evaluated both by comparing the models with tidal estimates from in situ observations (at one site, see Appendix) and by complex demodulation of the altimeter time series themselves after the predicted tide was removed. Neither method indicated any uncertainty greater than the base level of 2 to 3 cm.

Appendix: Tides

As noted in the text, aliasing of the barotropic tides because of imperfect tidal models is an issue that needs evaluation. However, for the sites being discussed, we found only a possible effect of no more than several centimeters. An inverted echo sounder record, as shown by Cartwright [1982], can however give an independent estimate of the tides and in Table 3 we compare the amplitude and phase of five major constituents from the sounder at 164° E with the two tidal models supplied with the altimeter data: namely, the Cartwright and Ray model [1990], based on GEOSAT altimeter data, and the earlier Schwiderski model [1981] based on a collection of shoreline tidal measurements. The sounder data were analyzed using the Foreman [1977] program with the assumption of a mean surface sound velocity of 1540 m/s. Also included in the comparison is a tidal analysis from a pressure gauge, deployed by PMEL/NOAA, Seattle for the same time period and within one nautical mile of the sounder.

First we note the good agreement between the in situ methods: at worst a five cm. difference in amplitude and less than ten degrees in phase. The largest difference is with the M2 component, where the sounder may be influenced by baroclinic tides at that frequency. The comparison between the two in situ methods and the two tidal models indicate no large or systematic differences, confirming what was deduced from the altimeter record itself, that tidal aliasing could at best introduce an uncertainty of a few centimeters, even in this area of relatively large amplitude, deep water, tides.

Cartwright and Ray have recently made available a revised model calculation based on early Topex/Poseidon data. It does not suggest any substantial change at the locations of concern here. For example, the largest amplitude constituent considered, M2 at 164°E, is revised to 544.7 mm, 143°.

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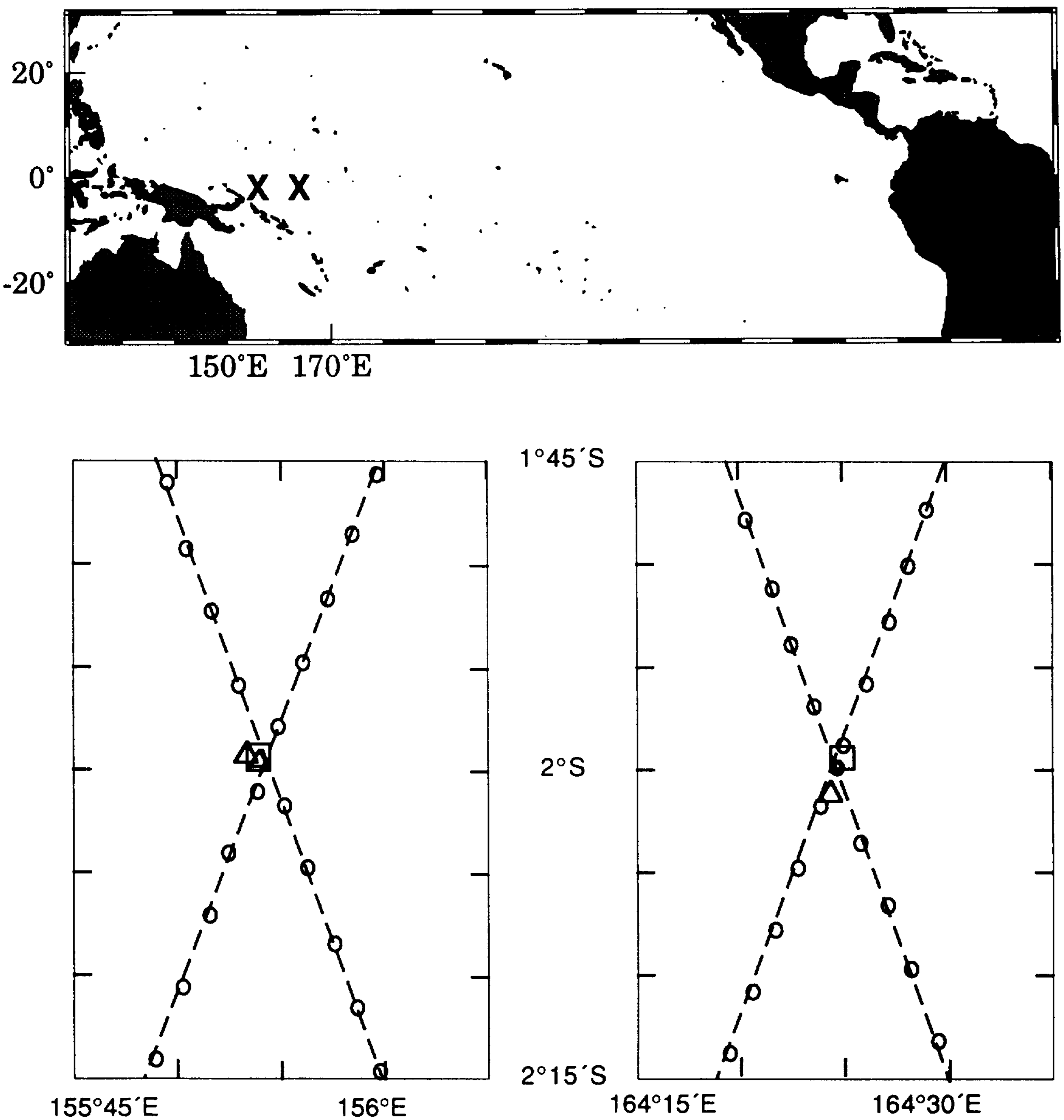

FIG. 1 Upper Panel: Site Location. Lower Panels: Location of Moorings (squares), Sounders (triangles) & Altimeter Tracks. Discrete altimeter reports along a typical path are located by circles. The passes crossing over the in situ observations are nos. 86 and 251 (left) and nos. 60 and 225 (right).

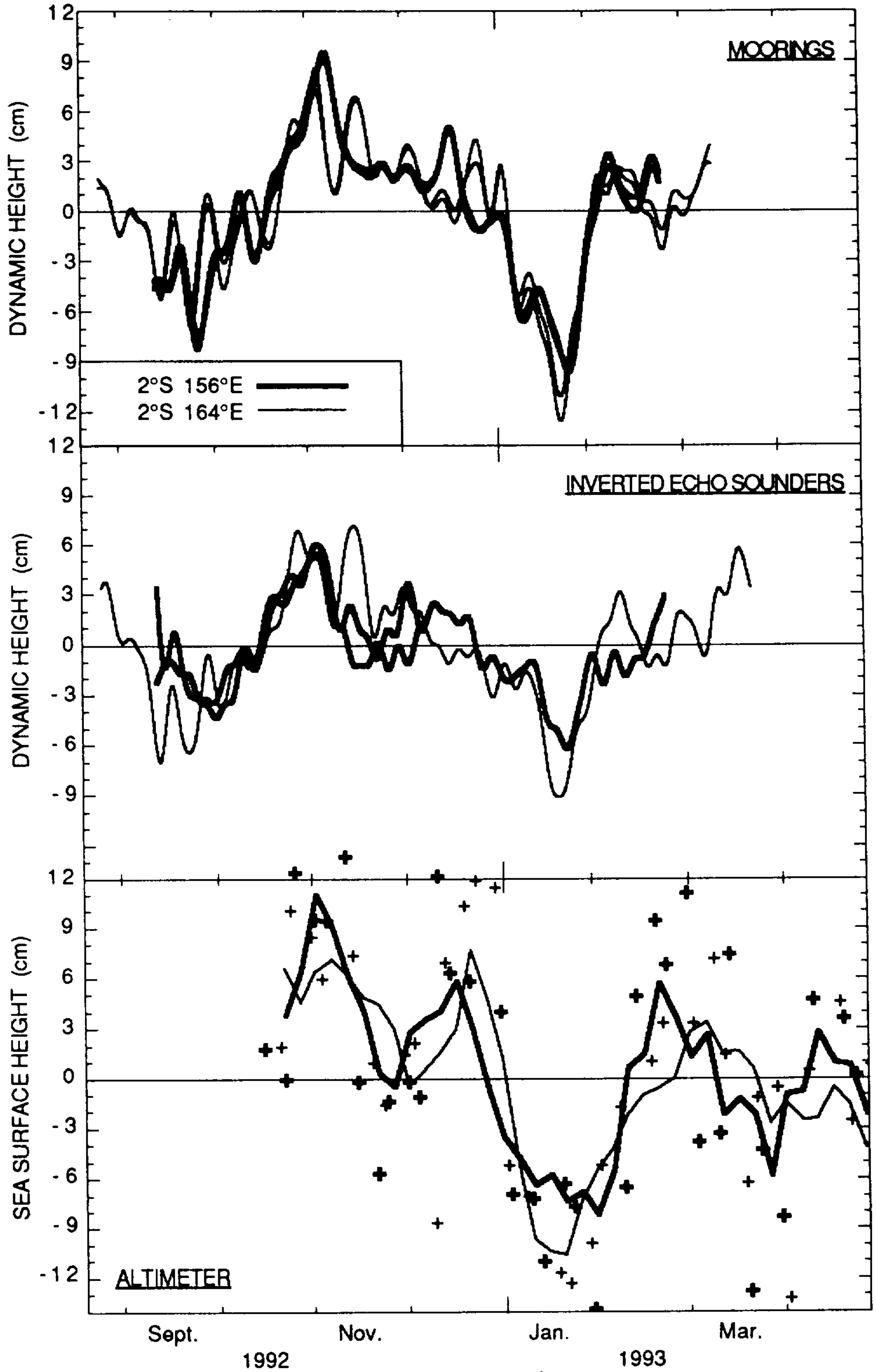

FIG. 2. Time Series of the Observations. The mean of each series has been removed. Upper Panel: Data from the two moorings after 5 day low-pass filtering. Both 0 re 1000 db and 0 re bottom are drawn, with only the slightest difference noticeable at the deeper site. Middle Panel: Data from the three sounders after 5 day low-pass filtering. After mid-Dec., only one of the sounders yielded data at 156°E. Bottom Panel: Two representations of the altimeter data. Plus signs are the individual observations after processing as described in the text. Solid lines are 20 day running mean averages computed every 5 days.

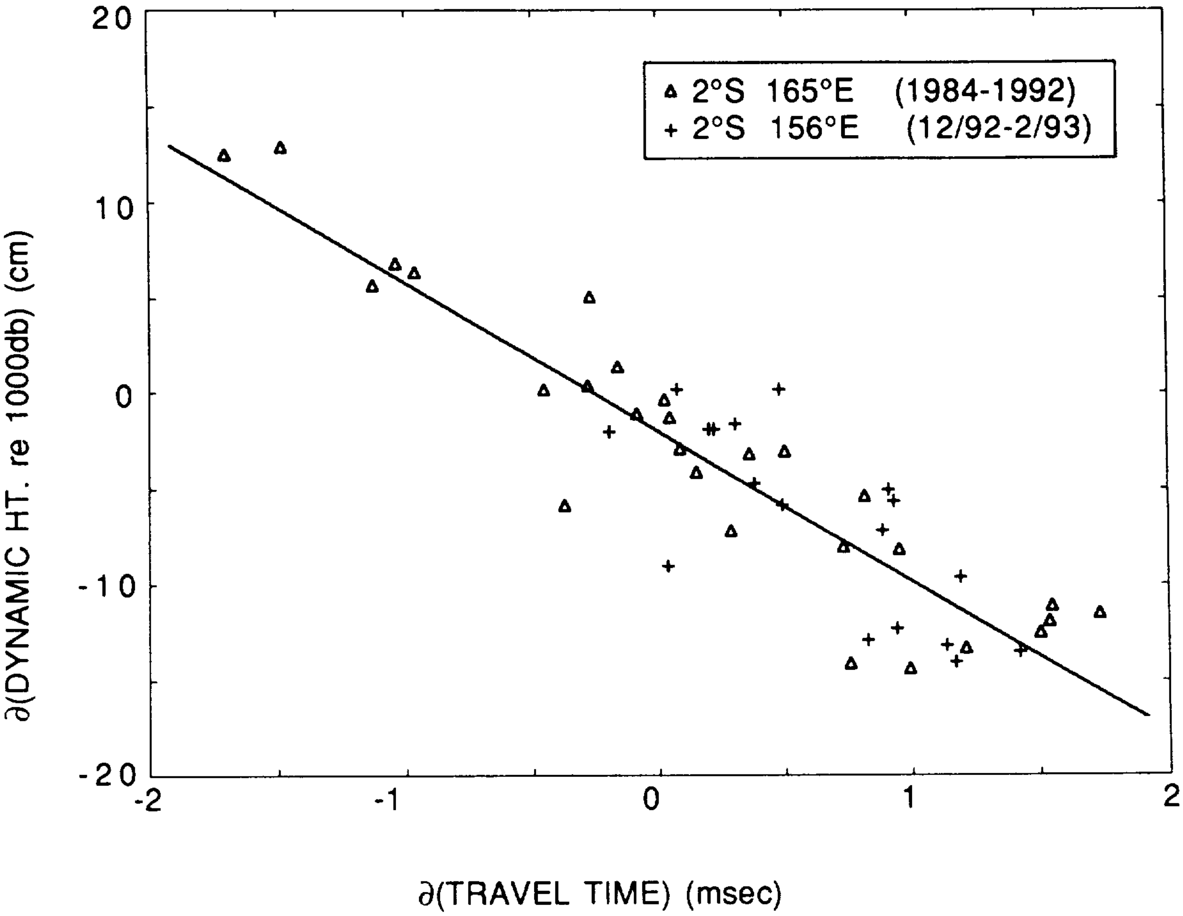

FIG. 3. Regression of the Dynamic Height of the Sea Surface on Acoustic Travel Time.

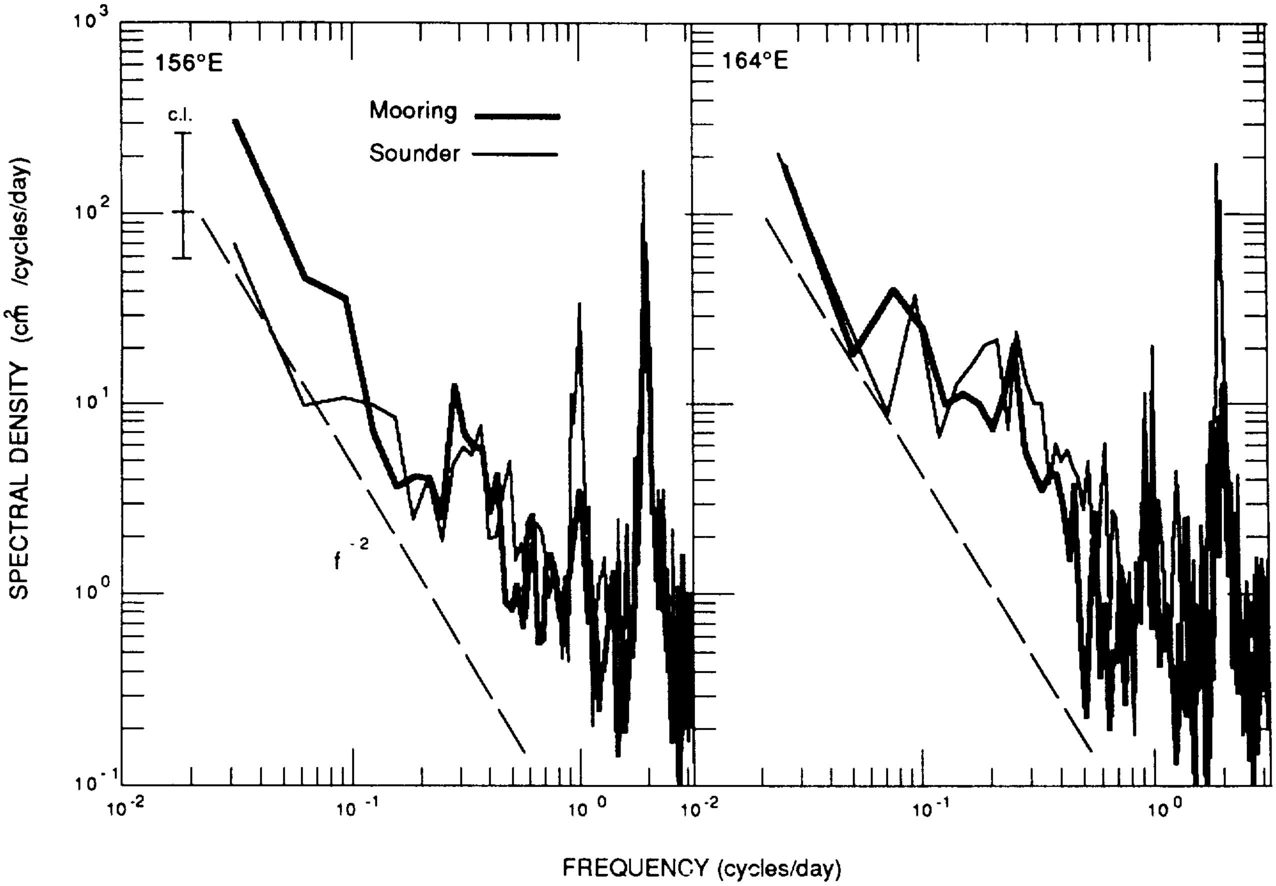

FIG. 4. Estimates of Spectral Density of the Sea Surface Height. Hourly data (except bihourly from sounder at 156°E) averaged over five frequency bands. The (95%) confidence limit (c.l.) shown is for 15 degrees of freedom (see text).

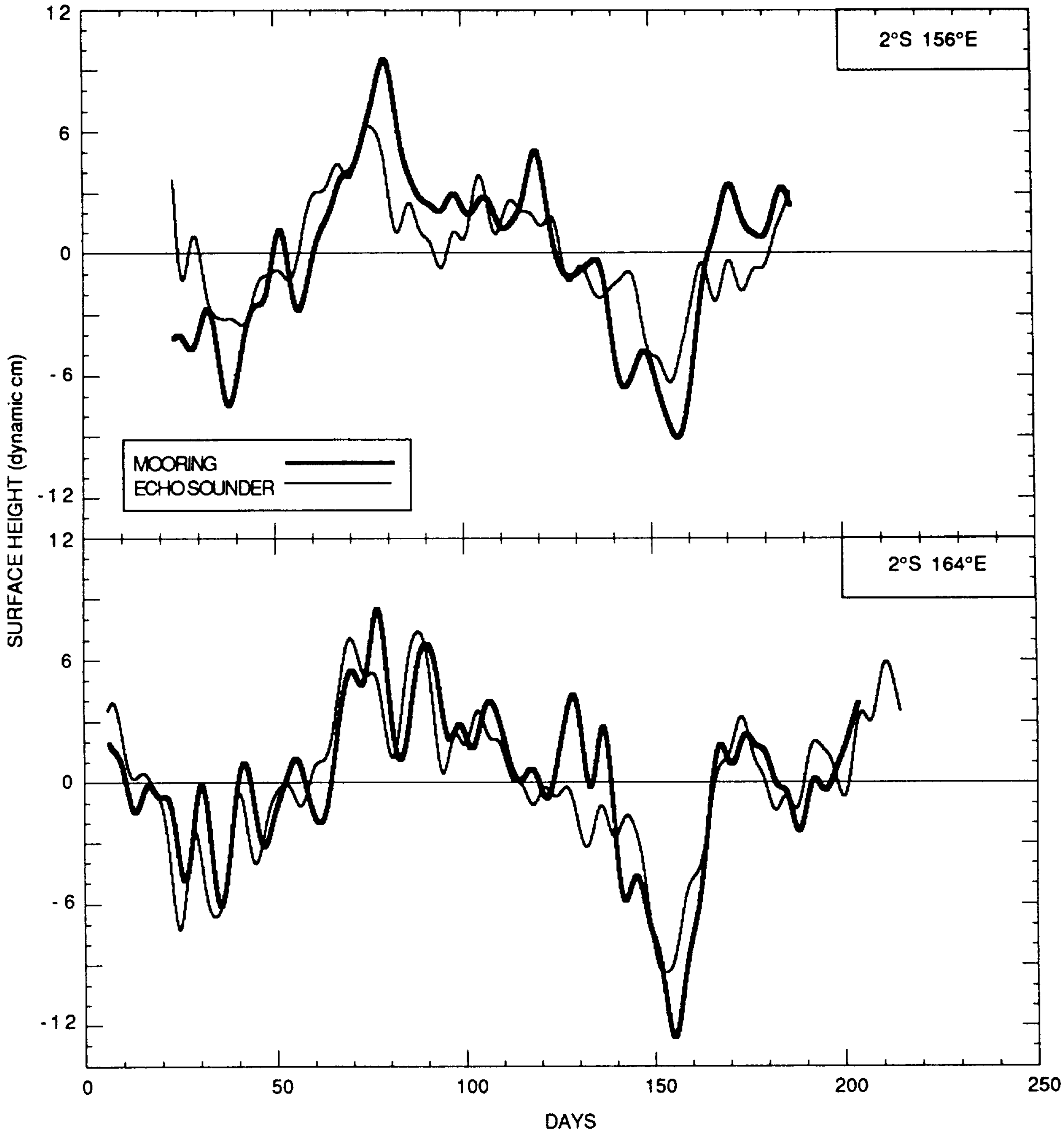

FIG. 5a. Comparison of the In Situ Observations at Both Sites. Redrawing of Figure 2 (upper two panels) to show tracking between sounder and mooring.

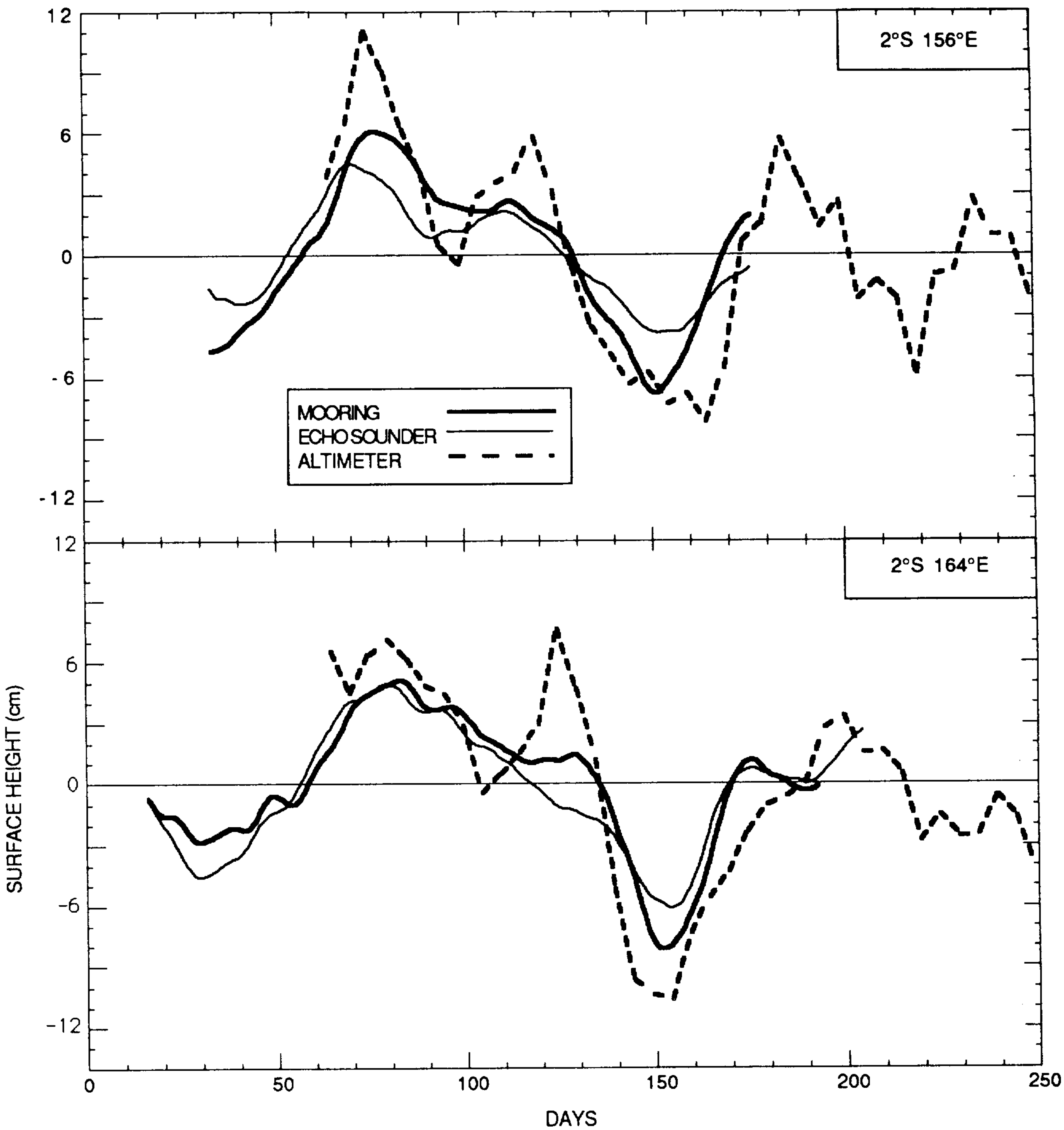

FIG. 5b. Comparison of the Three Observations at Both Sites. A running mean average over twenty days is plotted every five days.